AFRL-OSR-VA-TR-2015-0214

Diagnostics of Unseeded Air and Nitrogen Flows by Molecular Tagging

Richard Miles
TRUSTEES OF PRINCETON UNIVERSITY

07/21/2015
Final Report

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ RTE
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
04-08-2015	Final Performance	15-04-2012 to 14-04-2015

4. TITLE AND SUBTITLE
Diagnostics of Unseeded Air and Nitrogen Flows by Molecular Tagging

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA9550-12-1-0150

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Richard Miles

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
TRUSTEES OF PRINCETON UNIVERSITY
1 NASSAU HALL
PRINCETON, NJ 08544-0001 US

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AF Office of Scientific Research
875 N. Randolph St. Room 3112
Arlington, VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
AFOSR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
A DISTRIBUTION UNLIMITED: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This research effort has focused on the development of Femtosecond Laser Electronic Excitation Tagging (FLEET), a new molecular tagging diagnostic for subsonic, supersonic and hypersonic flows. A femtosecond laser is focused into a nitrogen containing flow of interest and creates a line of dissociated nitrogen molecules through the focal zone. The subsequent recombination of those nitrogen atoms occurs over tens of microseconds through a fluorescing upper electronic state, so the displacement and distortion of the line with the flow can be imaged with a time-gated camera. No seeding is required. The use of point tagging for the acquisition of full three dimensional velocity and acceleration data, line tagging the measurement of cross stream correlations and structure functions in free jets, and the tracking of cross patterns for the measurement of velocity and vorticity have all been examined in this effort. Megahertz rate imaging of patterns tagged at kilohertz rates have been demonstrated. The research has also addressed the perturbation that FLEET creates to the flow through the tagging

15. SUBJECT TERMS
nonequilibrium and aerothermodynamics, hypersonic and turbulence and boundary layer

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	UU		Richard Miles

19b. TELEPHONE NUMBER *(Include area code)*
609-258-5131

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

Final Report

Diagnostics of Unseeded Air and Nitrogen Flows by Molecular Tagging

FA9550-12-1-0150
Program Manager: Ivett Leyva

Richard Miles and Mikhail Shneider
Department of Mechanical and Aerospace Engineering
Princeton University

Abstract

This research effort has focused on the development of Femtosecond Laser Electronic Excitation Tagging (FLEET), a new molecular tagging diagnostic for subsonic, supersonic and hypersonic flows. A femtosecond laser is focused into a nitrogen containing flow of interest and creates a line of dissociated nitrogen molecules through the focal zone. The subsequent recombination of those nitrogen atoms occurs over tens of microseconds through a fluorescing upper electronic state, so the displacement and distortion of the line with the flow can be imaged with a time-gated camera. No seeding is required. The use of point tagging for the acquisition of full three dimensional velocity and acceleration data, line tagging the measurement of cross stream correlations and structure functions in free jets, and the tracking of cross patterns for the measurement of velocity and vorticity have all been examined in this effort. Megahertz rate imaging of patterns tagged at kilohertz rates have been demonstrated. The research has also addressed the perturbation that FLEET creates to the flow through the tagging mechanism.

Introduction

Measuring the transport properties of air is critical for the understanding of turbulence, for the understanding of boundary layer phenomena, for ground testing, and for computational model development and validation. Measurements need to be made in homogeneous turbulence, in turbulent near wall flows, in free shear layers, and in region where mixing is occurring. The challenge addressed in this research effort was the development of a method for molecular tagging in air and/or nitrogen which avoids seeding with either particles or foreign gases. The intention has been to establish a method that can follow the motion of the air or nitrogen in real time in order to establish transport properties and flow structure from the displacement and distortion of lines, crosses or more complex patterns.

The FLEET mechanism

The FLEET tagging process involves the interaction of a high intensity, short pulsed laser with nitrogen molecules, leading to multiphoton dissociation. The laser pulse is short enough to avoid avalanche breakdown and creates a uniform line of dissociated molecules through the focal zone. Figure 1 is a potential energy diagram for the nitrogen molecule. The energy of the laser photon is 1.55eV, and the emission following excitation can be broken into prompt emission (a few nanoseconds and primarily in the near ultraviolet) and delayed emission (tens of microseconds in primarily in the red to near infrared). The long time scale of the delayed emission is due to the time it takes for the dissociated nitrogen atoms to find each other and recombine. They combine into the nitrogen molecular B state, followed by fluorescence to the metastable A state. It is this delayed emission that is of use for FLEET. Figure 2 shows images of the lines tagged into air using a 30 cm focusing lens with various laser pulse energies at time delays of 2.5, 7.5 and 12.5 microseconds. Note that with higher laser pulse energy the tagged line not only gets longer, but the line center moves toward the laser source.

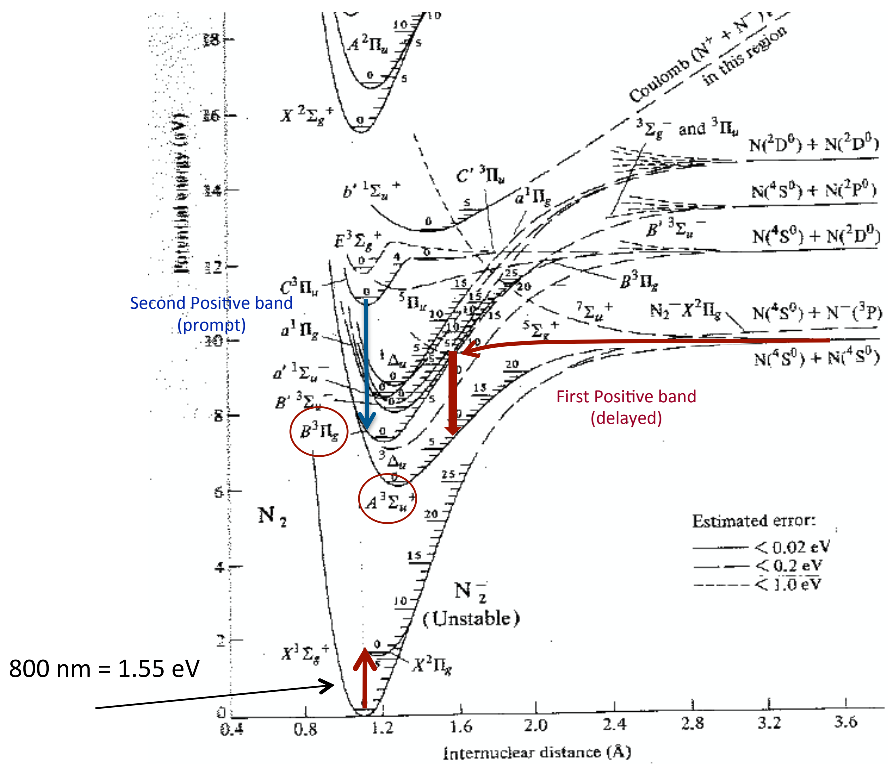

Figure 1: Potential energy diagram of nitrogen showing the "second positive" C to B state prompt emission and the recombination generated "first positive" B to A state delayed emission.

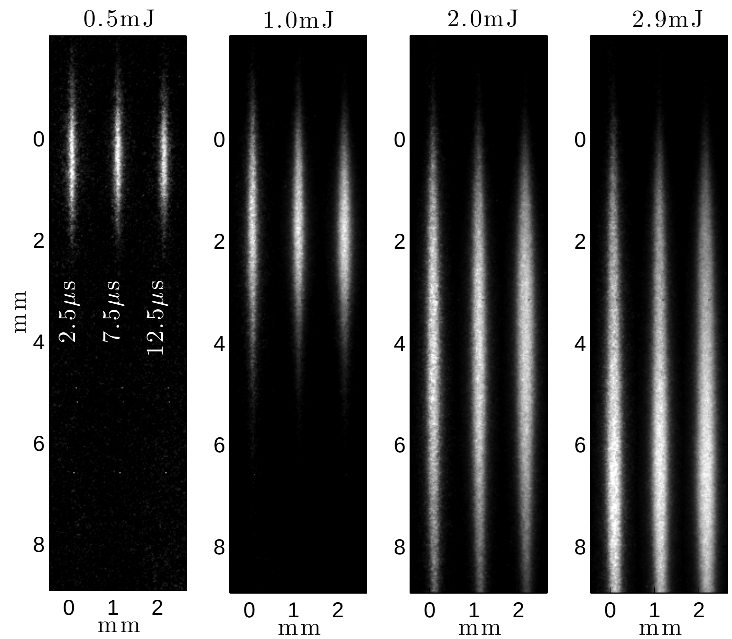

Figure 2: FLEET lines at three delays written with different 50 fsec pulse energies focused into 1 atmosphere pressure air with a 300 mm lens. The emission shows the increased intensity and line emission displacement toward the laser source with laser pulse energy.

Figure 3 presents normalized scatter plots of the total FLEET emission intensity as a function of laser pulse energy for nitrogen and air, showing an initial highly nonlinear increase in emission intensity at low laser pulse energy followed by a linear increase at higher pulse energies. The shift of the central position of the line toward the laser source is indicated by the color variation. The lines in nitrogen are approximately 20 times brighter than in air and the line center location shift with energy is less than air. This shift may be due to Kerr self focusing effects that increase with laser pulse energy and lead to self guiding filamentation and fluorescence clamping at the higher energies.

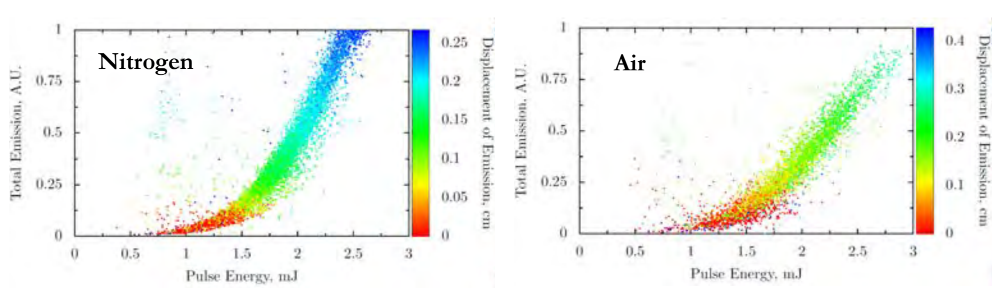

Figure 3: Scatter plots of FLEET in nitrogen (left) and air (right) with pulse energy. The color code indicates the displacement of the emission toward the laser source.

The dynamics of the dissociation process are, as yet, not well understood. One or a combination of three mechanisms can be occurring: 1) multiphoton ionization of N_2 followed by dissociative recombination of N_2^+, 2) direct multiphoton dissociation through a multiphoton transition to a dissociative or predissociative electronic state, and 3) multiphoton excitation of a stable electronic state of N_2 followed by dissociation by collisions of two of these excited molecules (energy pooling). The dissociation energy of nitrogen is 9.79 eV, more than six times the energy of the 800 nm photon from the femtosecond laser, so all of there process involve a highly nonlinear interaction and only occur in the region of the laser focus where the intensity is high enough to drive such processes. The ionization threshold lies 15.5 eV above the ground state. The dissociative and predissociative states of N_2 lie more than 12 eV, above the ground state, and the energy pooling A state is about 6.5 eV above the ground state. Thus we would expect that dissociation by dissociative recombination of N2+ requires at least ten photons to be absorbed simultaneously, direct dissociation can occur with 8 or more photons, and energy pooling may be achieved with 5 or more photons. Of course, once some transfer of energy to the molecule has occurred, the dissociation process itself may involve multiple steps, possibly including dissociation to excited atomic species or relaxation to energy pooling states.

Some understanding of the dissociation process can be inferred from measurements of the FLEET line strength along with simultaneous measurements of planar Rayleigh scattering in the low pulse energy regime, where negligible Kerr self focusing is occurring. Figure 4 shows the FLEET signal intensity along the center of a line tagged with 320 μJ laser pulse as well as the apparent temperature along that centerline determined using Planar Rayleigh Scattering and assuming atmospheric pressure and no dissociation. The FLEET intensity profile follows the apparent temperature profile almost exactly, and this property is maintained for at least the next 50 microseconds. Both of these curves fit well to the laser intensity through the focal zone if that intensity is raised to the 20th power, as indicated in the figure. This relationship between the FLEET intensity and the laser intensity suggests a 10 photon interaction, assuming the nitrogen atom recombination is a three body interaction, which is proportional to the square of the atomic number density. This is consistent with dissociative recombination of N2+ as the primary mechanism for the generation of the atomic species.

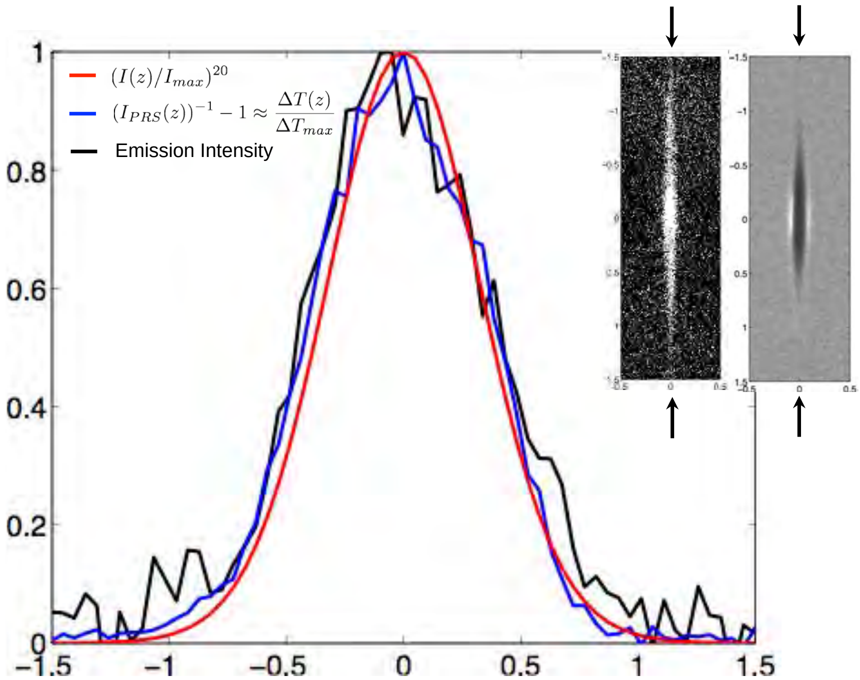

Figure 4: FLEET emission intensity along the tagged line along with the apparent temperature profile and the laser intensity profile raised to the 20th power.

Further understanding of the tagging and recombination processes can be accomplished using both planar Rayleigh scattering and line images of depolarication Rayleigh scattering. The experimental set up for depolarization Rayleigh imaging is shown in Figure 5. A frequency doubled, well polarized Nd:YAG laser beam passes through the FLEET tagged volume and both polarization components of the Rayleigh scattering from that beam are imaged by the camera, slightly offset from each other so both can be simultaneously recorded. Rayleigh scattering from molecules is weakly depolarized, whereas Rayleigh scattering from atoms is fully polarized, so by measuring the ratio of depolarized to polarized Rayleigh scattering, the depolarization fraction can be determined. Figure 6 shows the FLEET luminosity, the planar Rayleigh and the depolarized Rayleigh for a FLEET line written into 1 atm of pure nitrogen with a 320 µJ, 50 fsec laser pulse, taken one µsec after tagging. The two polarization components have been normalized to the same scale. Note that at the center of the line the perpendicular component is significantly reduced relative to the parallel component, indicating a large dissociation fraction.

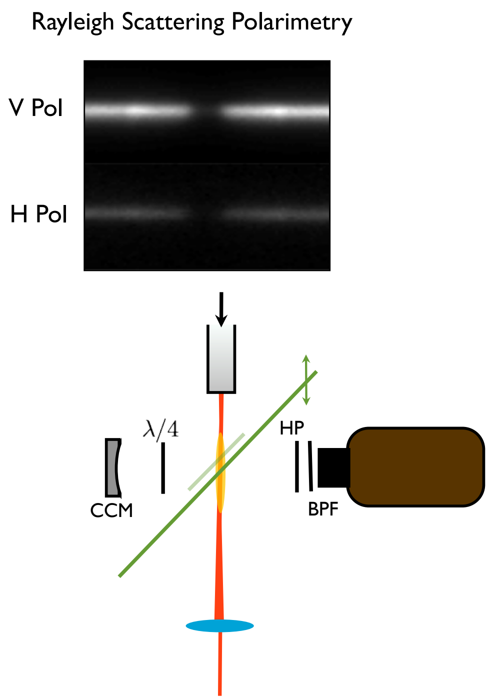

Figure 5: Experimental set up for simultaneous measurement of orthogonal polarizations of the Rayleigh scattering across the FLEET tagged line.

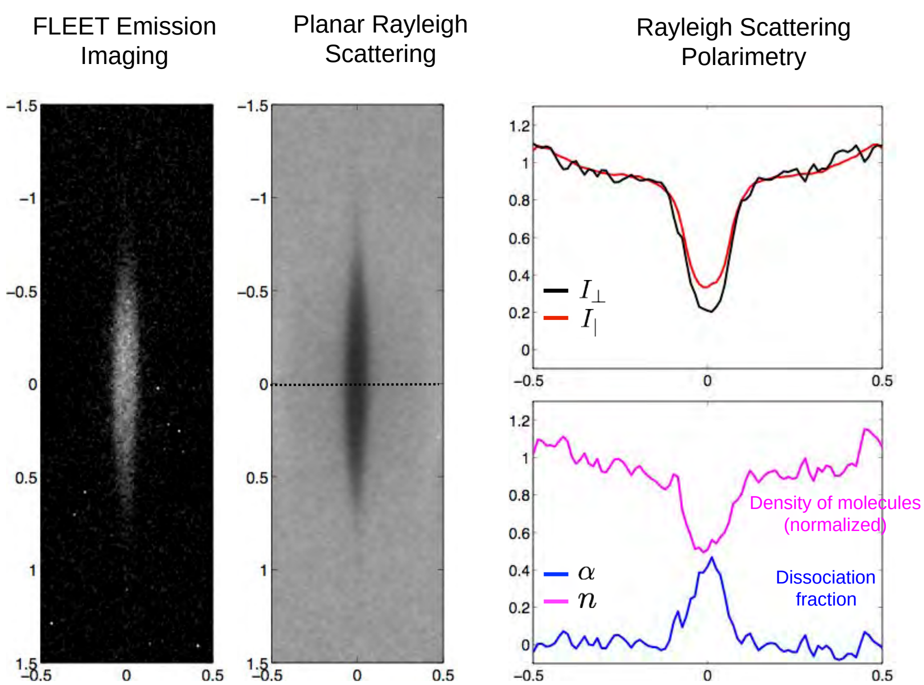

Figure 6: FLEET emission, Rayleigh planar image, and the transverse measurement of the polarization components across the FLEET line and the computed molecular density and dissociation fraction.

These measurements yield insight into the evolution of the center point of the tagging volume. A plot of the molecular nitrogen density, the dissociation fraction, the atomic nitrogen density and the FLEET emission is presented in figure 7. The mechanism for the emission at times below one microsecond appears to be different from the longer time emission, and may arise from energy transitions in molecular nitrogen.

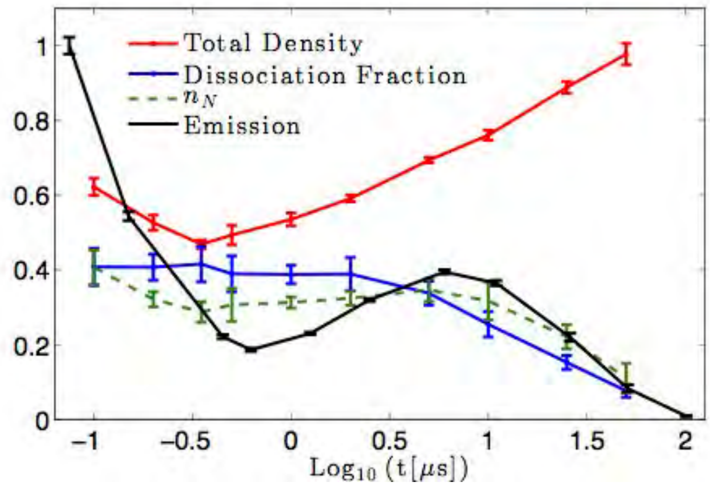

Figure 7: Time evolution of the density, dissociation fraction, nitrogen atomic number density and dissociation fraction.

Heating of the sample volume

A concern for the application of FLEET is the heating that occurs associated with the dissociation process. If too much heat is generated, that may perturb the sample and cause the tagging to no longer be an accurate measure of the flow transport properties. This has been studied using Rayleigh scattering and Rayleigh scattering polarimetry. Figure 8 shows the evolution of the Rayleigh scattering profile across a FLEET line formed by tightly focused 320 and 780 µJ, 50 nanosecond laser pulses in 1 atmosphere of air. The images record the evolution from 200 nsec to 100 µsec, and show the reduction in Rayleigh scattering at the center where the heating reduces the density as well as the increased Rayleigh scattering associated with the shock wave propagating away from the tagged region. If it is assumed that the air is not dissociated and that the pressure is uniform, then the temperature can be determined from the ideal gas law. With that assumption, the evolution of the temperature with time is plotted for pure nitrogen at 1 atmosphere for 320 and 780 µJ pulses as the dotted lines in Figure 9. That estimate must be corrected to take into account the reduced Rayleigh cross section of the atomic nitrogen, which is measured using the depolarization Rayleigh. That corrected temperature is shown in Figure 8 as the solid lines. The values at times below 2 microseconds are probably not correct because the pressure has not yet equilibrated.

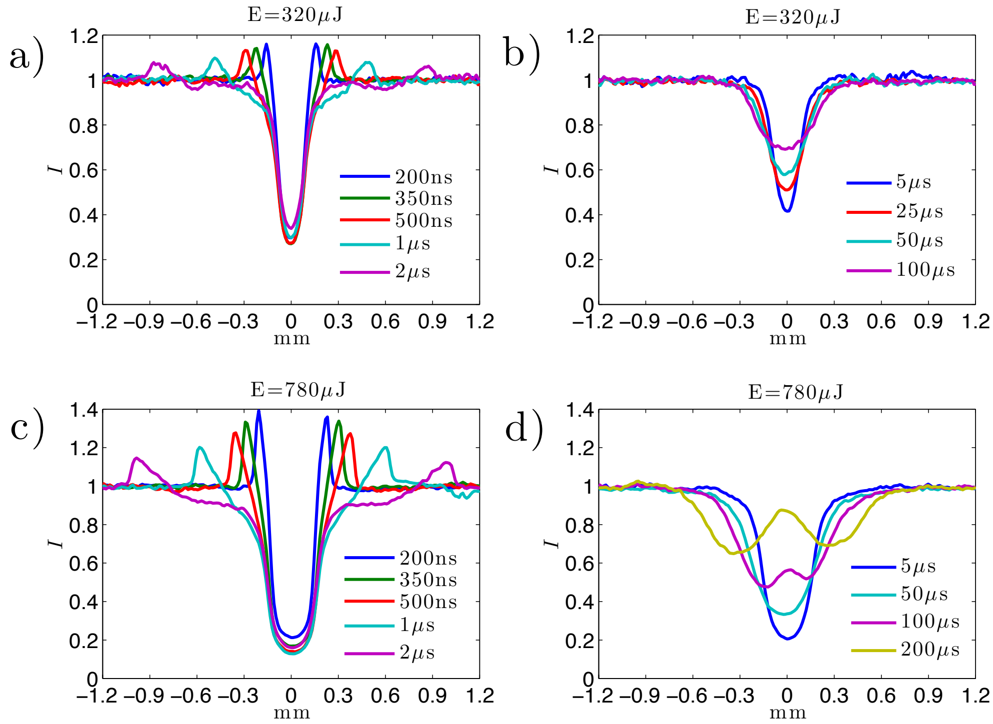

Figure 8: Time sequenced Rayleigh scattering profiles across the FLEET tagging region in air created with 320 and 780 μJ, 50 nanosecond laser pulses focused with a 175 mm lens.

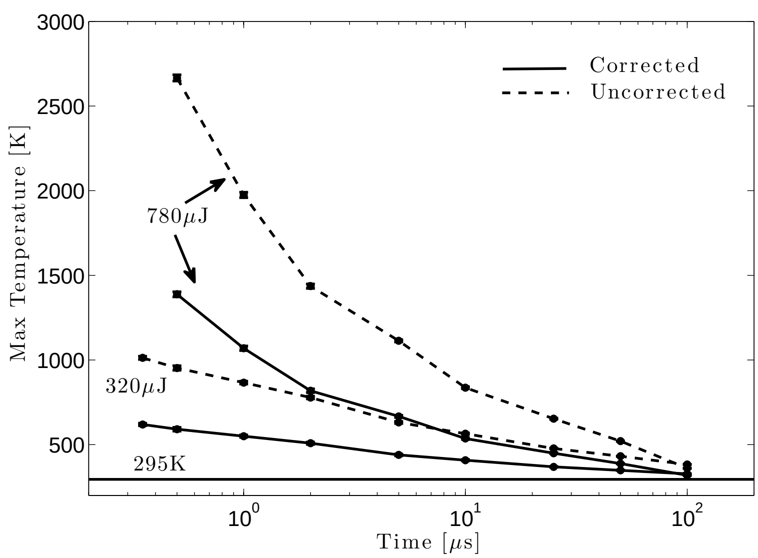

Figure 9: Apparent (dotted lines) and corrected (solid lines) temperature evolution from FLEET tagged regions created in nitrogen with 320 and 780 μJ, 50 nanosecond laser pulses focused with a 175 mm lens.

An alternative method of measuring the temperature is through the prompt emission. That emission occurs in the near ultraviolet within about ten nanoseconds of the tagging. The spectral features of that emission include rotational and vibrational transitions from the nitrogen C state to the nitrogen B state, which are called second positive emission. Although the distribution of states created by the femtosecond laser excitation is not related to the gas temperature in any easily predictable way, the rotational states in the upper electronic manifold equilibrate within a few hundred picoseconds, so the spectral signature of that band reflects the local gas temperature. Figure 10 shows the measured spectrum of the FLEET prompt emission in the 354-358 nm spectra region compared with the computed spectrum for various air temperatures. The 500K temperature curve most closely matches the FLEET spectrum. The FLEET tagging was done in air at 300K, so these data indicate an increase in temperature of 200K. Clearly an increase in temperature occurs and it is highly dependent on the laser pulse energy and the focusing.

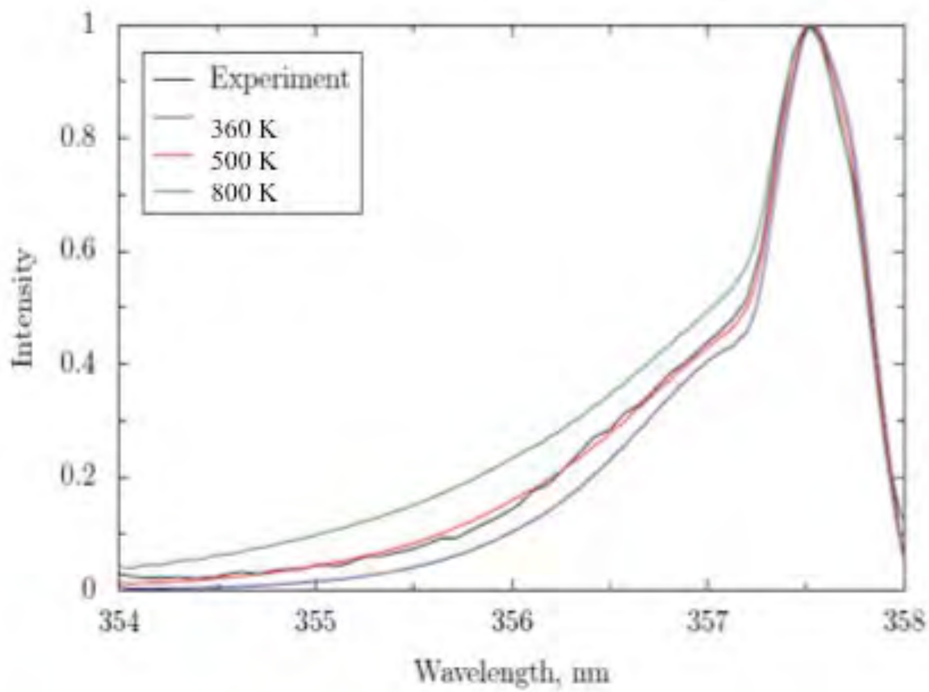

Figure 10: Prompt emission profile from FLEET showing the rotational structure measured and computed for 360K, 500K, and 800K.

Turbulence Measurements

The use of FLEET to measure turbulent flows is an important capability. An example of this is the measurement of turbulent properties of a free jet. At the exit of the jet, the fluctuations are very different at the center than they are near the edges. This can be seen by analyzing the transverse correlation functions at sequential locations across the jet. The transverse correlation function compares the velocity fluctuations at a chosen point with other points along a tagged line across the flow. It is normalized with 1

corresponding to 100% correlation, 0 corresponding to no correlation. Figure 11 shows the correlation function at various locations across the flow just downstream of the jet exit. The sharp peak corresponds to the presence of uncorrelated detection noise, which is an indication of the detector resolution. The wider region can shows that the correlation region near the edges of the jet is asymmetric and broad relative to the symmetric correlation at the core of the jet. Outside of the jet the correlations are spikes, indicating that the fluctuations are primarily due to the detection noise. By 40 diameters downstream the turbulence has become more homogeneous, and the fluctuations are uniform across the jet, as seen in Figure 12.

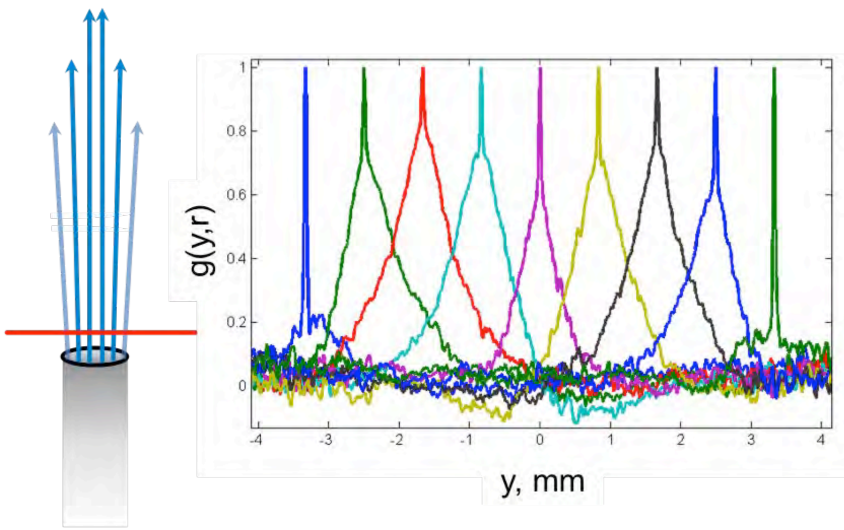

Figure 11: Transverse correlation functions at locations across the exit of an air free jet..

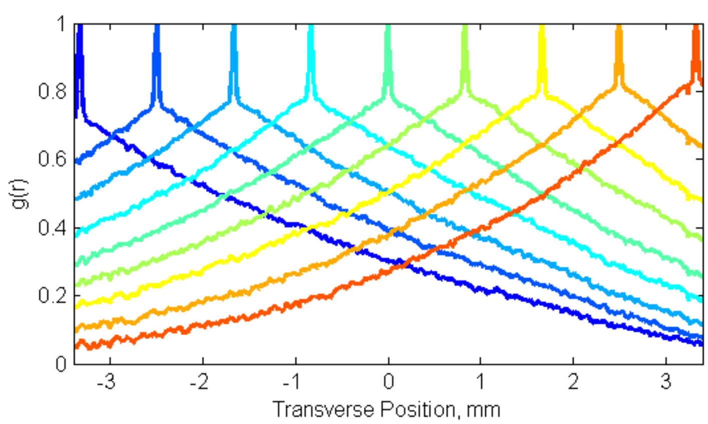

Figure 12: Transverse correlation functions 40 exit diameters downstream of the air jet exit.

Another representation of the properties of the turbulence is the transverse structure function.

$$S_p^{\perp}(r) = \langle |u(y+r) - u(y)|^p \rangle$$

where u(y) is the stream wise velocity at the point y along the line and p is the order of the structure function. For homogeneous turbulence the second order structure function has a slope of 2/3 assuming Kolmogorov scaling or 0.7 if intermittency is included. Figure 13 shows the measurement of the second order structure function 40 diameters downstream in the free jet. The FLEET measurement follows the Kolmogorov scaling until about 4mm, below which the curve diverges. This small scale region may be affected by the increased temperature. Further research on this topic is underway.

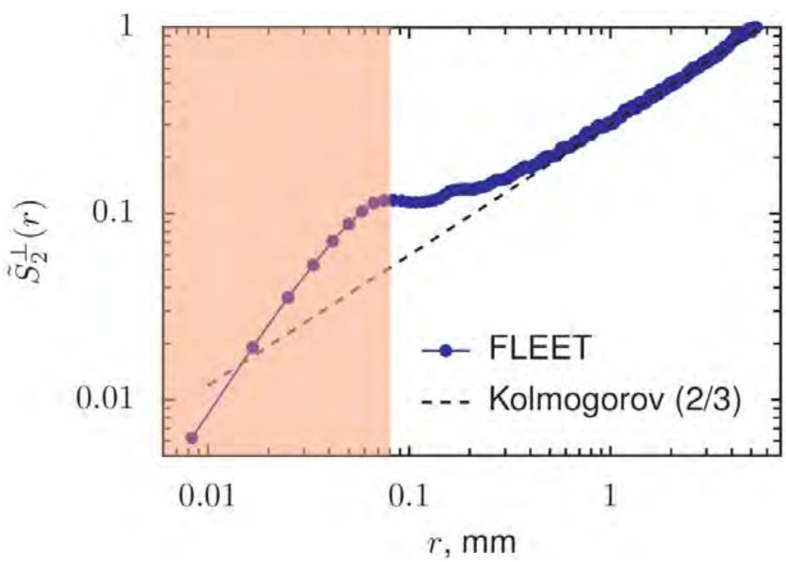

Figure 13: Second order structure function for turbulent free jet taken 40 diameters downstream.

Pattern Tracking

One of the useful properties of FLEET is the ability to write more complex patterns into a flow that provide further information regarding transport properties. An example of the is the writing of a cross into the flow. In this case the motion of the crossing point yields the vector velocity and the rotation of the cross gives the vorticity. Work on this capability has been undertaken in supersonic free jet and wind tunnel configurations Figure 14 shows the motion of a cross tagged into Mach 2.6 air in a small in-draft supersonic facility. These images show a single cross as it propagates in the core of the flow taken by multiple gating of the camera intensifier.

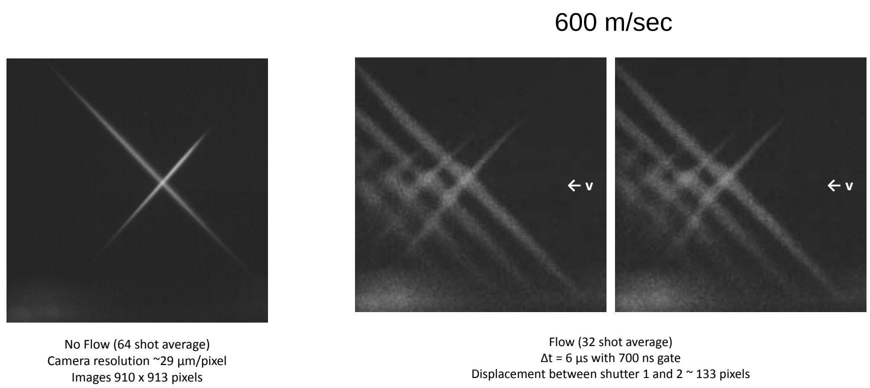

Figure 14: FLEET cross tagged into a Mach 2.6 in-draft air flow showing sequential time gated images of the motion of the cross from which the velocity vector and the vorticity can be determined.

Collaborations

Air Force Research Laboratory (Dr. James Gord)

Princeton student Nick DeLuca visited that laboratory and conducted that work together with staff from AFRL and Spectral Energies. Work there employed the high-energy femtosecond laser at that laboratory for characterization of the FLEET tagging with increasing energy and the use of FLEET for the measurement of the exit velocity from a pulsed detonation test duct.
That work also addressed the use of the boresight configuration for the measurement of point displacement. Figure 15 shows the configuration for those tests and the time delayed images. This configuration is of interest for the application of FLEET as an air data system for flight vehicles.

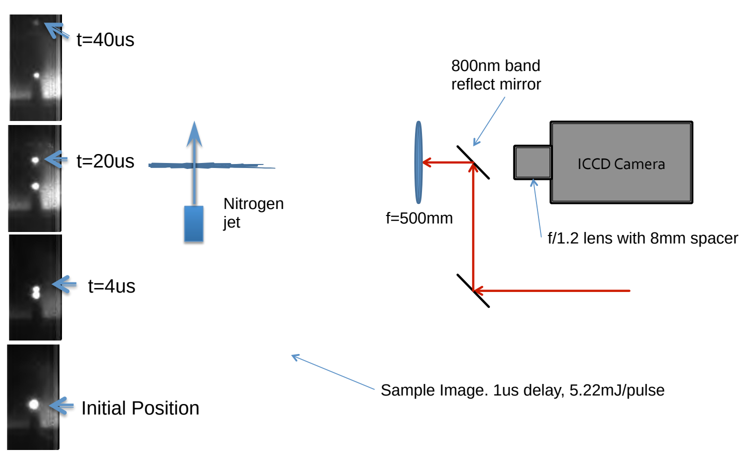

Figure 15: Boresight FLEET configuration and displacement measurement experiment at AFRL

NASA Langley (Dr. Paul Danehy)

Princeton student Christopher Peters is supported by a NASA Space Technology Research Fellowship and worked at NASA Langley on this collaboration. This collaboration has focused on the application of FLEET to measurements in the National Trans-sonic Facility, which operates with cold nitrogen. Tests have been undertaken with cold atmospheric pressure nitrogen and include work on the evaluation of commercial camera capabilities for capturing the flow features. Experiments with NASA personnel at Princeton provided the first measurement of three dimensional motion of a flow using simultaneous orthogonal projections of the motion of FLEET velocity and acceleration by following small points whose displacement is captured by imaging both projection onto a single camera image with multiple time delayed gating. A pair of those time sequenced images is shown in Figure 16.

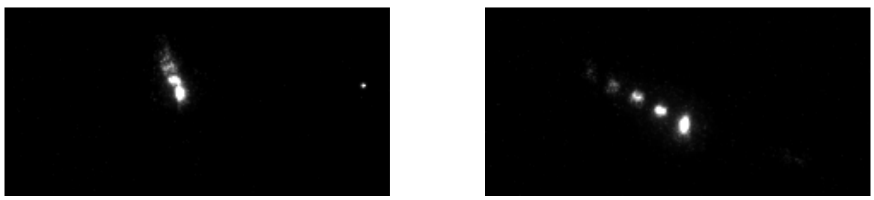

Figure 16: Time sequenced orthogonal images of the motion of a FLEET generated point in an air jet showing the capability to follow in real time the motion of the point in three dimensions for the determination of vector velocity and acceleration.

Arnold Engineering Development Center and Plasma TEC (Dr. Eric Marineau)

A Phase I SBIR effort under Plasma Tec, Inc, has been undertaken with the AEDC Tunnel 9 in Maryland. That effort has addressed the measurement of core and boundary layer properties in supersonic and hypersonic nitrogen flows. For this work the Princeton kHz laser system was transported to AEDC and operated to image flows in their nitrogen indraft tunnel. Figure 17 shows the camera location relative to the tunnel and a small subset of the images captured in those experiments. Images were taken at 1 kHz rates and each image contained multiple images of the same line across the boundary layer imaged multiple times at 3 microsecond intervals. The center image is the non displaced line that is used to determine the initial location for the measurement of displacement.

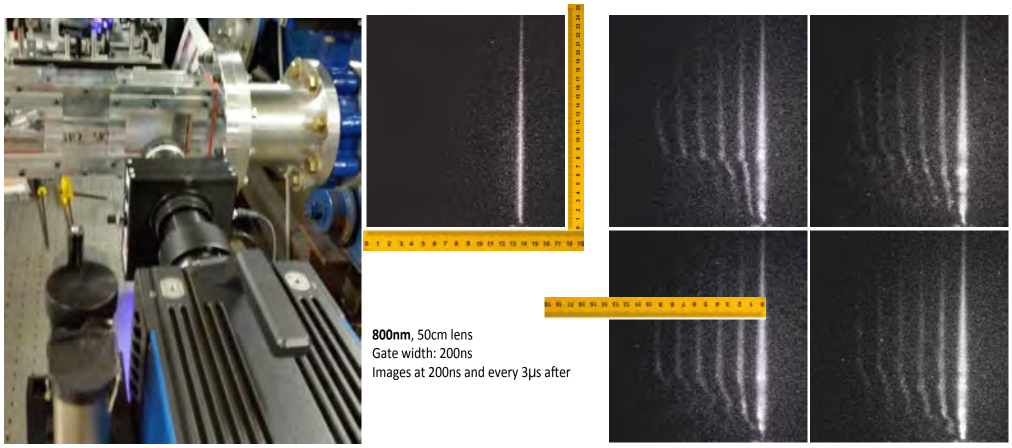

Figure 17: FLEET measurements of the flow from the wall to the core of the in-draft Mach 2.8 nitrogen facility at AEDC.

Kharkiv National Automobile and Highway University, Department of Applied Mathematics, Ukraine (Prof. Albina Tropina)

This collaboration seeks to understand the effects of energy addition on the properties of turbulence. The FLEET tagging process generates heating at a scale that falls within the inertial Kolmogorov range of fully developed turbulence. The modeling uses a Fourier analysis to examine the evolution of that energy with time. Figure 18 presents preliminary results of that modeling effort, showing the evolution of the second order structure function at times after energy is added at 20 times the Kolmogorov scale. Note that the perturbation that occurs proceeds toward the smaller scale with time, and the distortion of the structure function resembles the distortion measured by FLEET and shown in figure 13.

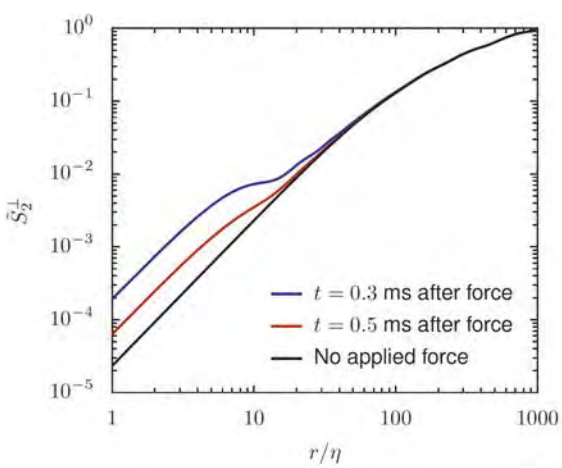

Figure 18: Modeled evolution of energy added to turbulent flow at 20 time the Kolmogorov scale.

MetroLaser (Dr. Jacob George)

A Phase I SBIR with NASA Ames has been initiated to examine the use of FLEET and other approaches for the measurement of flow properties in a hypersonic arc jet facility.

Summary

FLEET has been further developed under this research project, with results providing quantitative information on the dissociation mechanisms and thermal impact of FLEET on the sample volume and the potential for FLEET to measure properties of turbulence in both air and nitrogen flows. The work has been extended to collaborative efforts with AFRL and NASA, providing further insight on the use of FLEET for a variety of applications including application to national ground test facilities and establishing the potential for applications for flight data.

Personnel

Graduate Students Completed

- James Michael Ph.D. 2012 (Assistant Professor, Iowa State University)
- Nicholas DeLuca M.S. 2014 (active duty US Marine Corps)

Current Graduate Students (and support or partial support sharing)

- Nathan Calvert (NSF)
- Tat Loon Chng (Princeton Plasma Science and Technology Fellow)
- Matthew Edwards (NSF)
- Chris Limbach (NDSEG)
  - Accepted Post Doc at Colorado State Fall 2015
- Sean McGuire (Princeton Plasma Science and Technology Fellow)
  - Accepted Post Doc Ecole Centrale Paris, France Fall 2015
- Christopher (Petey) Peters (NSTRF)
- Yibin Zhang (NDSEG)

Research Scientists supported

- Dr. Mikhail Shneider,

Technical Support

- Nick Tkach

Peer Reviewed Publications

- M. N. Shneider and R.B. Miles., "Laser Induced Avalanche Ionization in Gases or Gas Mixtures with Resonantly Enhanced Multiphoton Ionization or Femtosecond Laser Pulse Pre-Ionization." Physics of Plasmas Volume: 19 Issue: 8 Article Number: 083508 Published: AUG 2012
- M. N. Shneider and R.B. Miles.,"Coherent Microwave Radiation from a Laser Induced Plasma," Applied Physics Letters 101, 264105 (2012) (published on-line Dec 27, 2012)
- Dogariu, Arthur; Shneider, Mikhail N.; Miles, Richard B., "Versatile radar measurement of the electron loss rate in air," Applied Physics Letters Volume: 103 Issue: 22 Article Number: 224102 Published: NOV 25 2013
- S. McGuire and R. Miles, "Collision induced ultraviolet structure in nitrogen radar REMPI spectra," The Journal of Chemical Physics 141, 244301 (2014); doi: 10.1063/1.4904261 View online: http://dx.doi.org/10.1063/1.4904261
- Edwards, M., Dogariu, A. and Miles, R. "Simultaneous Temperature and Velocity Measurement in Unseeded Air Flows with FLEET," AIAA Journal, Volume 51, Paper J053685
- Miles, Richard B., "Optical diagnostics for high-speed flows," Progress in Aerospace Sciences, Volume: 72 Special Issue: SI Pages: 30-36 Published: JAN 2015\
- Miles RB, Michael JB, Limbach CM, McGuire SD, Loon Chng T, Edwards MR, DeLuca NJ, Shneider MN, Dogariu A. 2015 New diagnostic methods for laser plasma- and microwave-enhanced combustion. *Phil. Trans. R. Soc. A* **373**: 20140338. http://dx.doi.org/10.1098/rsta.2014.0338

Conference Manuscripts

- J. B. Michael; M. R. Edwards; A. Dogariu; R. B. Miles, "Velocimetry by Femtosecond Laser Electronic Excitation Tagging (FLEET) of Air and Nitrogen", AIAA-2012-1053, AIAA Aerospace Sciences Meeting, Nashville, TN, Jan 9-12, 2012
- S. McGuire; S. Zaidi; A. Dogariu; P. Howard; R. B. Miles, "Measuring the Velocity of a Supersonic Airflow with Laser Ionization Tagged Radar Anemometry (LITRA)", AIAA-2012-0989, AIAA Aerospace Sciences Meeting, Nashville, TN, Jan 9-12, 2012
- Matthew Edwards, Arthur Dogariu, Richard Miles, "Simultaneous Temperature and Velocity Measurement in Unseeded Air Flows with FLEET," 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, 2013, 10.2514/6.2013-43
- Richard Miles, "Femtosecond Laser Electronic Excitation Tagging (FLEET) for Imaging Flow Structure in Unseeded Hot or Cold Air or

Nitrogen," 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, 2013, 10.2514/6.2013-340

- Sean McGuire, Sohail Zaidi, Arthur Dogariu, Richard Miles, Chris Hovde, "The intrinsic phase shift and its effect upon the measurement of airflow velocities using LITRA," 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, 2013, 10.2514/6.2013-430
- Tat Loon Chng, James Michael, Arthur Dogariu, Sohail Zaidi, Richard Miles, "Towards Quantitative Flame Species Concentration Measurements Using Radar REMPI," 51st AIAA Aerospace Sciences Meeting including the New Horizons Forum and Aerospace Exposition, 2013, 10.2514/6.2013-433
- Sean McGuire, Tat Chng, Richard B. Miles, "Nanosecond time-resolved 2 + 2 Radar REMPI measurements performed in molecular nitrogen," (AIAA 2013-2760) 44th AIAA Plasmadynamics and Lasers Conference, 2013, 10.2514/6.2013-2760
- Nathan Calvert, Arthur Dogariu, Richard B. Miles, "FLEET Boundary Layer Velocity Profile Measurements," (AIAA 2013-2762) 44th AIAA Plasmadynamics and Lasers Conference, 2013, 10.2514/6.2013-2762
- Richard B. Miles, "Optical Diagnostics for High-Speed Flows," (AIAA 2013-2610), 43rd Fluid Dynamics Conference, 2013, 10.2514/6.2013-2610
- Christopher Limbach, Richard Miles, "Simultaneous Temperature, Density and Velocity Measurements in Laser-Generated Plasmas by Rayleigh and Filtered Rayleigh Scattering (AIAA 2014-0143) 52nd Aerospace Sciences Meeting, 2014, 10.2514/6.2014-0143
- Tat Loon Chng, Richard Miles, "Absolute concentration measurements of atomic oxygen in a flame using radar REMPI" (AIAA 2014-1360) 52nd Aerospace Sciences Meeting, 2014, 10.2514/6.2014-1360
- Albina Tropina, Mikhail N. Shneider, Richard Miles, "Turbulent Cascade Process in Arc Driven Plasma Channels" (AIAA 2014-0668) 52nd Aerospace Sciences Meeting, 2014, 10.2514/6.2014-0668
- Sean McGuire, Richard B. Miles, "Radar REMPI measurements of N2 rotational temperature," (AIAA 2014-2114) 45th AIAA Plasmadynamics and Lasers Conference, 2014, 10.2514/6.2014-2114
- Christopher Limbach, Richard B. Miles, "Rayleigh and Thomson Scattering Diagnostics of Laser Air Sparks: A Testbed for Tailoring Laser Plasmas," (AIAA 2014-2538) 45th AIAA Plasmadynamics and Lasers Conference, 2014, 10.2514/6.2014-2538
- Paul M. Danehy, Brett F. Bathel, Nathan D. Calvert, Arthur Dogariu, Richard B. Miles, "Three Component Velocity and Acceleration Measurement Using FLEET," (AIAA 2014-2228) 30th AIAA Aerodynamic Measurement Technology and Ground Testing Conference, 2014,10.2514/6.2014-2228
- Jacob George, Tom P. Jenkins, Richard B. Miles, "Diagnosis of High Speed Flows using Filtered Rayleigh Scattering," (AIAA 2014-2231) 30th

AIAA Aerodynamic Measurement Technology and Ground Testing Conference, 2014, 10.2514/6.2014-2231

- Nathan D. Calvert, Arthur Dogariu, Richard B. Miles, “2-D Velocity and Vorticity Measurements with FLEET,” (AIAA 2014-2229) 30th AIAA Aerodynamic Measurement Technology and Ground Testing Conference, 2014, 10.2514/6.2014-2229
- Nicholas J. DeLuca, Richard B. Miles, Waruna D. Kulatilaka, Naibo Jiang, James R. Gord, “Femtosecond Laser Electronic Excitation Tagging (FLEET) Fundamental Pulse Energy and Spectral Response,” (AIAA 2014-2227) 30th AIAA Aerodynamic Measurement Technology and Ground Testing Conference, 2014, 10.2514/6.2014-2227
- Richard B. Miles, “Atmospheric Pressure Plasma Based Flame Control and Diagnostics,” (AIAA 2015-0157) 53rd AIAA Aerospace Sciences Meeting, 2015, 10.2514/6.2015-0157
- Sean McGuire, Arthur Dogariu, Tat Chng, Richard B. Miles,“Methods for Enhancing Radar REMPI Sensitivity,” (AIAA 2015-0933)53rd AIAA Aerospace Sciences Meeting, 2015, 10.2514/6.2015-0933
- Christopher Limbach, Richard B. Miles, “Characterization of Dissociation and Gas Heating in Femtosecond Laser Plasma with Planar Rayleigh Scattering and Rayleigh Scattering Polarimetry,” (AIAA 2015-0932) 53rd AIAA Aerospace Sciences Meeting, 2015, 10.2514/6.2015-0932
- Matthew R. Edwards, Christopher Limbach, Richard B. Miles, Albina Tropina, “Limitations on High-Spatial Resolution Measurements of Turbulence Using Femtosecond Laser Tagging,” (AIAA 2015-1219) 53rd AIAA Aerospace Sciences Meeting, 2015, 10.2514/6.2015-1219
- Tat Loon Chng, Richard B. Miles, Understanding the Impact of Buffer Gases on the Radar REMPI Diagnostic (AIAA 2015-2803) 46th AIAA Plasmadynamics and Lasers Conference, 2015, 10.2514/6.2015-2803
- Nathan Calvert, Arthur Dogariu, Matthew Edwards, Richard B. Miles, Density Scaling and Calibration of FLEET Temperature Measurements (AIAA 2015-2564) 31st AIAA Aerodynamic Measurement Technology and Ground Testing Conference, 2015, 10.2514/6.2015-2564
- Christopher J. Peters, Paul M. Danehy, Brett F. Bathel, Naibo Jiang, Nathan Calvert, Richard B. Miles, Precision of FLEET Velocimetry using High-Speed CMOS Camera Systems, 31st AIAA Aerodynamic Measurement Technology and Ground Testing Conference, 2015, 10.2514/6.2015-2565

AFOSR Deliverables Submission Survey

Response ID:4768 Data

1.

1. Report Type

Final Report

Primary Contact E-mail
Contact email if there is a problem with the report.

miles@princeton.edu

Primary Contact Phone Number
Contact phone number if there is a problem with the report

609-258-5131

Organization / Institution name

Princeton University

Grant/Contract Title
The full title of the funded effort.

Diagnostics of Unseeded Air and Nitrogen Flows by Molecular Tagging

Grant/Contract Number
AFOSR assigned control number. It must begin with "FA9550" or "F49620" or "FA2386".

FA9550-12-1-0150

Principal Investigator Name
The full name of the principal investigator on the grant or contract.

Richard B. Miles

Program Manager
The AFOSR Program Manager currently assigned to the award

Ivett Leyva

Reporting Period Start Date

04/15/2012

Reporting Period End Date

04/14/2015

Abstract

This research effort has focused on the development of Femtosecond Laser Electronic Excitation Tagging (FLEET), a new molecular tagging diagnostic for subsonic, supersonic and hypersonic flows. A femtosecond laser is focused into a nitrogen containing flow of interest and creates a line of dissociated nitrogen molecules through the focal zone. The subsequent recombination of those nitrogen atoms occurs over tens of microseconds through a fluorescing upper electronic state, so the displacement and distortion of the line with the flow can be imaged with a time-gated camera. No seeding is required. The use of point tagging for the acquisition of full three dimensional velocity and acceleration data, line tagging the measurement of cross stream correlations and structure functions in free jets, and the tracking of cross patterns for the measurement of velocity and vorticity have all been examined in this effort. Megahertz rate imaging of patterns tagged at kilohertz rates have been demonstrated. The research has also addressed the perturbation that FLEET creates to the flow through the tagging

mechanism. Collaborations have been undertaken with the Air Force Research Lab, NASA, the Arnold Engineering Development Center and with international partners.

Distribution Statement
This is block 12 on the SF298 form.

Distribution A - Approved for Public Release

Explanation for Distribution Statement
If this is not approved for public release, please provide a short explanation. E.g., contains proprietary information.

SF298 Form
Please attach your SF298 form. A blank SF298 can be found here. Please do not password protect or secure the PDF The maximum file size for an SF298 is 50MB.

SF 298.pdf

Upload the Report Document. File must be a PDF. Please do not password protect or secure the PDF . The maximum file size for the Report Document is 50MB.

Final Report.pdf

Upload a Report Document, if any. The maximum file size for the Report Document is 50MB.

Archival Publications (published) during reporting period:

M. N. Shneider and R.B. Miles., "Laser Induced Avalanche Ionization in Gases or Gas Mixtures with Resonantly Enhanced Multiphoton Ionization or Femtosecond Laser Pulse Pre-Ionization." Physics of Plasmas Volume: 19 Issue: 8 Article Number: 083508 Published: AUG 2012

M. N. Shneider and R.B. Miles.,"Coherent Microwave Radiation from a Laser Induced Plasma," Applied Physics Letters 101, 264105 (2012) (published on-line Dec 27, 2012)

Dogariu, Arthur; Shneider, Mikhail N.; Miles, Richard B., "Versatile radar measurement of the electron loss rate in air," Applied Physics Letters Volume: 103 Issue: 22 Article Number: 224102 Published: NOV 25 2013

S. McGuire and R. Miles, "Collision induced ultraviolet structure in nitrogen radar REMPI spectra," The Journal of Chemical Physics 141, 244301 (2014); doi: 10.1063/1.4904261 View online: http://dx.doi.org/10.1063/1.4904261

Edwards, M., Dogariu, A. and Miles, R. "Simultaneous Temperature and Velocity Measurement in Unseeded Air Flows with FLEET," AIAA Journal, Volume 51, Paper J053685

Miles, Richard B., "Optical diagnostics for high-speed flows," Progress in Aerospace Sciences, Volume: 72 Special Issue: SI Pages: 30-36 Published: JAN 2015\

Miles RB, Michael JB, Limbach CM, McGuire SD, Loon Chng T, Edwards MR, DeLuca NJ, Shneider MN, Dogariu A. 2015 New diagnostic methods for laser plasma- and microwave-enhanced combustion. Phil. Trans. R. Soc. A 373: 20140338. http://dx.doi.org/10.1098/rsta.2014.0338

Changes in research objectives (if any):

Change in AFOSR Program Manager, if any:

Extensions granted or milestones slipped, if any:

AFOSR LRIR Number

LRIR Title

Reporting Period

Laboratory Task Manager

Program Officer

Research Objectives

Technical Summary

Funding Summary by Cost Category (by FY, $K)

	Starting FY	FY+1	FY+2
Salary			
Equipment/Facilities			
Supplies			
Total			

Report Document

Report Document - Text Analysis

Report Document - Text Analysis

Appendix Documents

2. Thank You

E-mail user

Jul 15, 2015 13:35:20 Success: Email Sent to: miles@princeton.edu